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ILLUMINATING ENGINEERING SOCIETY

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OCTOBER, 1937

32 VICTORIA STREET
LONDON SW1

NOTES ON RECENT MEETINGS AND EVENTS

Applications for Membership.

At the opening meeting of the Society, held on October 12, 1937, the names of the following applicants for membership were presented:—

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Shapcott, C. .....Woodmansterne, Park Estate, Dronfield, DERBYSHIRE.

(Continued on p. 142)

A DIRECT READING PHOTOELECTRIC TRICHROMATIC COLORIMETER

by G. T. WINCH, A.M.I.E.E. *(Member)*, and EVELYN H. PALMER, B.Sc.

(Communication No. 224 from the Staff of the Research Laboratories of the General Electric Company Limited, Wembley, England.)

ABSTRACT.

Details are given of the principle, development and construction of a new type of photoelectric colorimeter, which indicates the trichromatic co-ordinates directly on an RGB system closely and linearly related to the C.I.E., XYZ system. The method of calibration is described, and the Appendix contains a worked example of the transformation from the RGB to the XYZ system, together with a nomogram for the rapid conversion from one system to the other. Reference is made to the many applications of this instrument.

(1) Introduction.

There has always been a limited demand for a means of measuring colour, but in the past this has chiefly been associated with the measurement of the colour of fabrics, painted surfaces, coloured glasses, etc.

With the rapid development and increasing applications of electric discharge lamps, particularly the new developments in connection with luminescent materials, there is a growing demand for simple and rapid means of measuring and specifying the colour and colour rendering properties of the light from any light source.

It is obviously desirable, if possible, to make or refer such measurements to the C.I.E. trichromatic system[1], but visual trichromatic colorimeters available on the market for making such determinations, such as the Guild[2] or Donaldson[3] colorimeter, are unsuitable for rapid commercial operation by unskilled observers.

The experimental photoelectric instrument[4] described below, has been developed for making such routine commercial measurements of colour, and indicates the colour in terms of RGB units on a system closely and linearly related to the XYZ system agreed by the Int. Comm. on Illumination (C.I.E.). As a result of the experience gained in this development, there seems to be a reasonable likelihood of improving the photocell-filter combinations to approximate more nearly the sensitivities required to give direct reading on the C.I.E. XYZ system. However, with the present instrument, having once calibrated it, and determined the constants, the transposition from the RGB to the XYZ co-ordinates can be accomplished in a few seconds from a nomogram[5] relating the two systems. (See Appendix.)

Although this instrument was originally developed particularly for measuring the colour and colour rendering properties of light sources, with suitable photometric auxiliaries, it can be adapted to measure the colour of fabrics, paints, filters, etc.

(2) Principle of Operation.

The present instrument utilises the principle proposed by Bloch[6], and referred to elsewhere[7], particularly by J. Guild in these "Transactions"[8].

It has been shown that the essential requirements for a photoelectric colorimeter are three photocells with suitable filter combinations, having spectral response functions identical with the $\bar{x}$, $\bar{y}$, $\bar{z}$, of the C.I.E. standard observer, shown in Fig. 1, or with

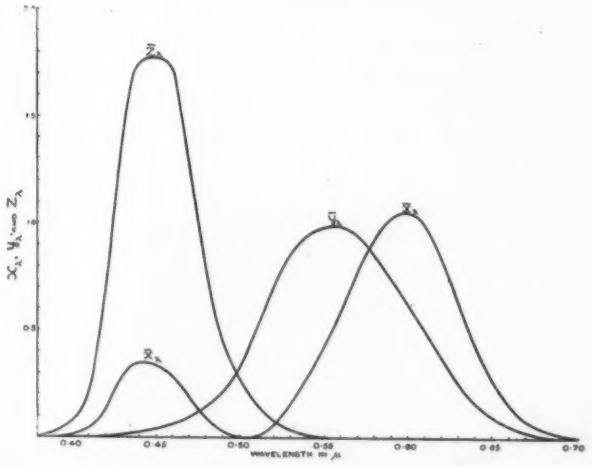

Fig. 1.—Distribution coefficients of the C.I.E. System.

corresponding functions expressed on any other trichromatic system. The currents from three such receivers would be proportional to the XYZ trichromatic coefficients of the C.I.E. system, or the RGB coefficients of any other convenient system related to the C.I.E. system by known linear transformations.

(3) Design of Colorimeter.

It has generally been assumed that these requirements cannot be realised in practice, and this is still probably true if colorimetry of the highest accuracy is required; but recent improvements in the quality of selenium rectifier type photoelectric cells, together with advances in the matching of colour filters to them, have made it possible to apply the principle in a simple manner to obtain results of sufficient accuracy for most commercial purposes.

In addition, by a special optical system, three reflecting galvanometers are arranged to project line images, so that with the galvanometers at zero these images form an equilateral triangle. The light to be analysed for colour, falling uniformly on the three photocell-filter components, the cells of which are connected to the three galvanometers, causes deflec-

tions resulting in movement of the three line images in a direction perpendicular to their length, towards the centre of the triangle. By adjusting the total amount of light incident on the cells, there is one position where the three lines must intersect at one point. For any other coloured light source the point of intersection will be different; but because the three deflections are proportional, respectively, to $\bar{r}$, $\bar{g}$, $\bar{b}$, and the sum of the perpendiculars on the sides from any point in an equilateral triangle is a constant, at the point of intersection, the three deflections satisfy the unit equation $r+g+b=1$, and give directly the R, G, B, values of the light source under test without calculation.

(4) Details of Apparatus.

The photoelectric colorimeter shown in Fig. 2 consists of the following components:

(a) PHOTOCELL-FILTER UNIT.

This comprises three rectangular selenium rectifier type photocells supplied by Salford Electrical Inst., Ltd. These have sensitive surfaces approximately

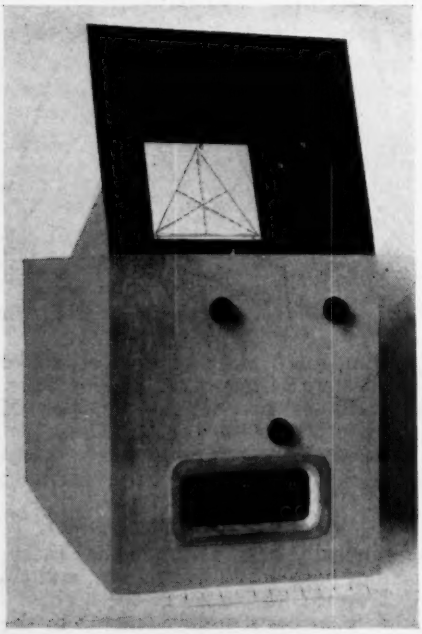

Fig. 2.—Photograph of Colorimeter.

16 × 35 mm., and are mounted in adjacent holders, together with their respective colour filters, as shown in Fig. 3. Although, so far, it has not been possible to make photocell-filter combinations having spectral sensitivities exactly the same as the C.I.E. $\bar{x}$, $\bar{y}$, $\bar{z}$, distribution coefficients, it has been possible to approximate to these requirements. One practical combination which has been used successfully results

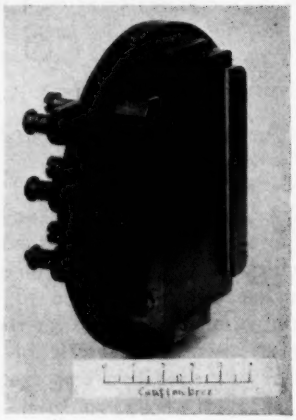

Fig. 3.—Photograph of holder carrying three photocells and respective filters.

in an RGB system linearly related to the XYZ system and defined by the following equations:

$$R = 0.9111X + 0.0926Y - 0.0037Z$$
$$G = -0.0330X + 1.0182Y + 0.0148Z$$
$$B = 0.0102X - 0.0476Y + 1.0374Z$$

The spectral locus is everywhere within the triangle as shown in Fig. 4.

Actually the above filter combinations were built up from a series of Wratten gelatine filters, Schott and Calorex glass, the latter to exclude radiation out-

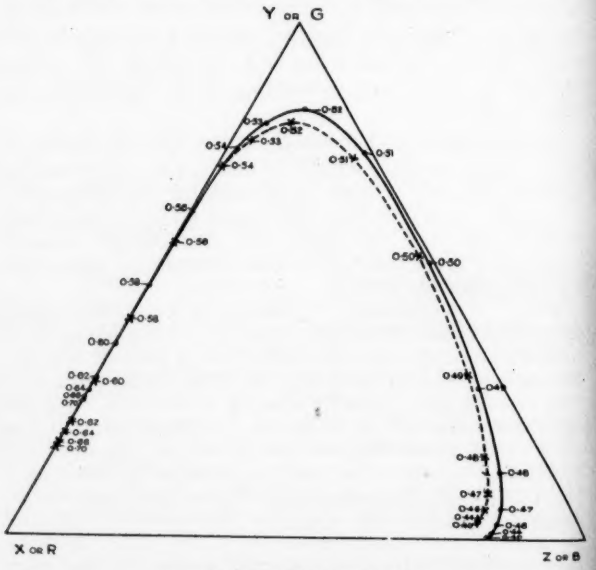

Fig. 4.—Diagram showing the spectral locus on the XYZ and the RGB Systems.

side the visible spectrum. Unfortunately it was found that even with this precaution sufficient infra red radiation penetrated to the cells to cause errors larger than could be tolerated, and it therefore be-

came necessary to use a 2 cm. thickness of a 2 per cent. solution of Cupric Chloride" for this purpose.

Messrs. C. H. Beale and D. A. Crook, of Spicer Dufay (British), Ltd., have very kindly assisted us in this connection by making composite filters for this purpose, which have just come to hand.

(b) Galvanometers and Projection Unit.

The three Cambridge d'Arsonval type galvanometers used are all similar, having resistances of about 40 ohms and sensitivities of approximately 20 cm. per microamp at a metre. These are connected respectively across the three photocells. With this low external circuit resistance the response of the photocells is substantially linear, and as the angular movement utilised is arranged not to exceed a deflection of the order of 6 degrees, the tangent errors on the flat scale are negligible. The galvanometers are mounted, together with a special optical system, in the lower part of the colorimeter cabinet shown in Fig. 2. The optical arrangement for one galvanometer system is shown diagrammatically in Fig. 5.

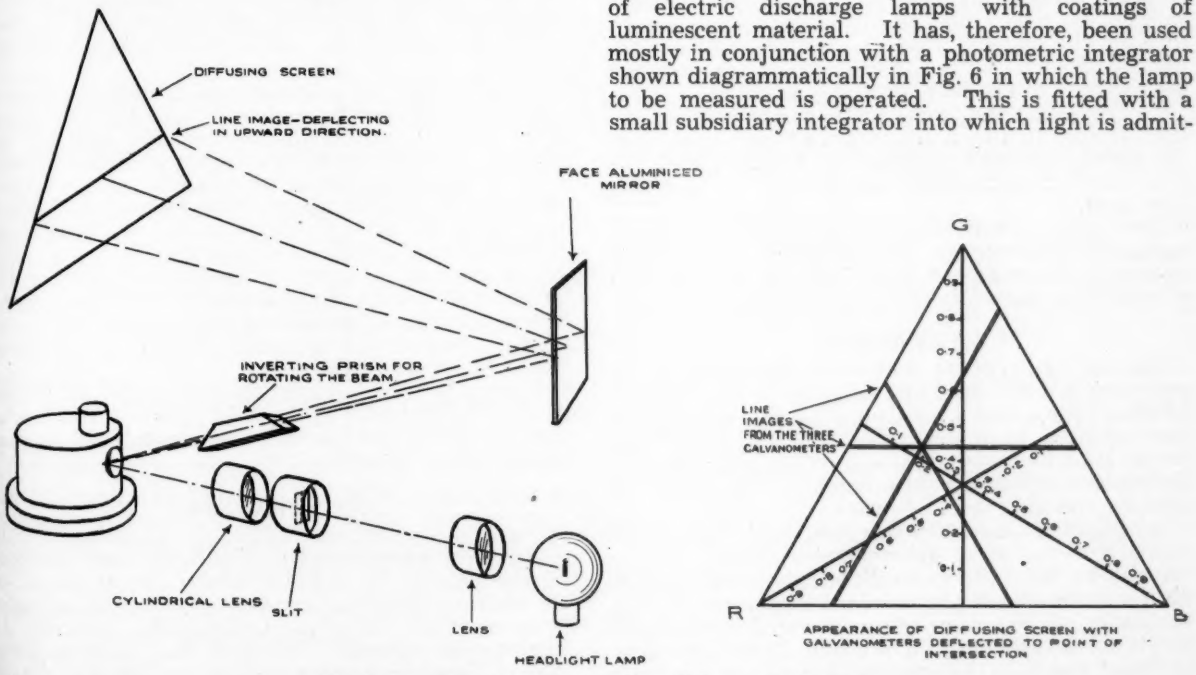

Fig. 5.—The Optical Arrangement of one Galvanometer System.

Light from the slit, on which is imaged the filament of a 48 watt motor-car headlight lamp, passes through a cylindrical lens on to the mirror of the galvanometer, so that an image of the slit is formed on the diffusing screen, shown in the upper section of the colorimeter. (Fig. 2.) An inverting prism inserted in the beam of light leaving the galvanometer mirror enables the beam to be rotated, and the angle between the image of the slit and slit itself to be varied as desired. In addition, in order to obtain the requisite galvanometer throw in a compact instrument, the beam reaches the diffusing screen via a face aluminised mirror.

The three galvanometers, together with their similar optical systems, are mounted so that with the galvanometers at zero the three line images rest on the three sides of the equilateral triangle drawn on the diffusing glass screen. Shunting resistances are provided to enable the relative sensitivities of the galvanometers to be adjusted for calibration purposes. By connecting the galvanometers in parallel with resistances of the order of 400 ohms (critical damping resistance), and the photocell across the required portion of this resistance, the damping of the galvanometers is not seriously increased.

(c) Photometric Unit for Illuminating P.E. Cells.

Units (a) and (b) can be adapted to any colorimetric measurements and, therefore, are used with a photometric set-up suited to the particular problem. As explained in the introduction, this colorimeter was developed mainly in connection with the measurement of the colour and colour rendering properties of electric discharge lamps with coatings of luminescent material. It has, therefore, been used mostly in conjunction with a photometric integrator shown diagrammatically in Fig. 6 in which the lamp to be measured is operated. This is fitted with a small subsidiary integrator into which light is admitted through an aperture in the main integrator, screened from the source under test. The amount of light entering the subsidiary integrator is controlled by a micrometer shutter, and the photocell-filter unit is screened from this aperture and only receives integrated light.

By this arrangement the average colour of a light source can be measured.

If it is required to measure the colour of light emitted by a source in one particular direction, then

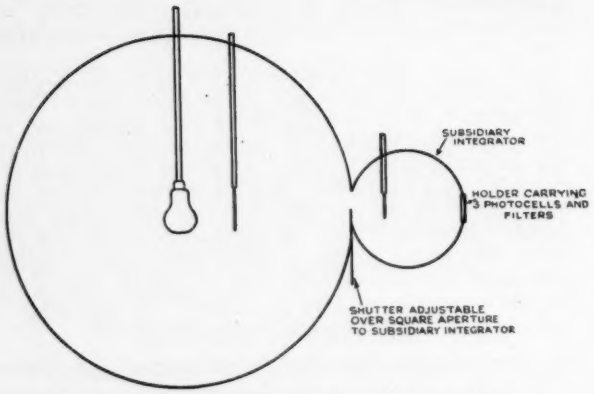
SUBSIDIARY INTEGRATOR
HOLDER CARRYING 3 PHOTOCELLS AND FILTERS
SHUTTER ADJUSTABLE OVER SQUARE APERTURE TO SUBSIDIARY INTEGRATOR

Fig. 6.—Diagram of Photometric Integrator Arrangement.

the photocell-filter unit need only be mounted normal to this direction, care being taken to ensure that the distribution of the light is uniform over the light sensitive areas of the three photocells. The illumination on the photocells can in this case be varied by altering the distance from the source, provided the distance is such that the distribution of light over the photocells will not be appreciably affected.

To determine the trichromatic co-ordinates of the light transmitted by a filter from a given illuminant, the above photometric set-up can be used with the filter inserted between the source and the photocell filter unit.

The colour of reflected light from fabric or other coloured surfaces can be measured by suitably arranging the reflected light from the specimen to illuminate uniformally the photocell-filter unit.

(5) Calibration.

The calibration of the colorimeter is carried out by reference to monochromatic radiation at wavelengths 0.6438μ, 0.546μ, and 0.436μ, obtained by isolating the mercury and cadmium lines from an electric discharge lamp by means of filters. The C.I.E. standard illuminants and a sodium laboratory type lamp are used for checking the calibration.

Initially it is necessary to adjust the relative sensitivities of the three galvanometers, and it is convenient for this purpose to illuminate the photocell-filter unit by one of the standard illuminants in the particular photometric set-up on which measurements are subsequently to be made. It will probably be found that i_B is the smallest of the three photocell currents, and therefore the sensitivity of the R and G components will probably need to be reduced. If, for example, the photometric integrating arrangement referred to in Section (4c) is being used, the standard illuminant would be operated in the integrator. The photocell sensitivities would then be adjusted until the trichromatic co-ordinates indicated by the point of intersection of the three line images on the diffusing screen are approximately the defined values of X, Y, and Z.

This procedure was followed originally with the experimental form of this apparatus, and no regular change in calibration has since been found to occur over a period of several months.

If it is required to find the relation between the two systems so that the values can be transposed, the observed R, G, B values and X, Y, Z co-ordinates of the three calibration points are equated and the equations solved. Where it is required to transpose rapidly from one system to another this can be successfully accomplished in a few seconds by reference to a nomogram constructed from a knowledge of the constants of the transposition equations. For the sake of completeness, in the Appendix to this paper, an example is worked out showing the method of carrying out the transposition and computing and constructing a nomogram for this purpose.

(6) Accuracy and Speed of Measurement.

The absolute accuracy of the measurements made on this instrument, using the early experimental photocell-filter units, was of the order of 0.01 to 0.02 in the value of the trichromatic coefficients. A large part of this error was traced to incomplete absorption by the filters of the infra-red radiation, and it is anticipated that when the new filters referred to in Section (4a) have been fitted these errors will be reduced.

Once the apparatus has been calibrated subsequent measurements can be made very rapidly, the actual time taken to adjust the shutter and read off the R, G, B co-ordinates being a matter of seconds. However, a certain amount of time is expended in setting up the light source, filters, or test specimen. When measuring the average colour of the light from tungsten filaments in clear or coloured bulbs, with lamps all of one type, the speed of operation is of the order of 50 to 100 per hour. Other classes of measurement, where the time of setting up is greater, will require a proportionately longer time, resulting in reduced speed of measurement.

If results are required to be transposed to the X, Y, Z co-ordinates of the C.I.E. system, this can be done in a few seconds on a nomogram such as that shown in the appendix.

(7) Applications.

The convenience and speed of operation of this colorimeter has enabled it to be used for a number of applications, in addition to the measurement of the colour and colour rendering properties of light from electric discharge lamps with coatings of luminescent material. Daylight blue bulb tungsten filament lamps have been measured in order to obtain data for a proposed specification, also colour filters, railway and traffic signal glasses, and coloured globes have been tested to specification, when illuminated by known illuminants. Recently it has been found useful for measuring the colour of the fluorescent screens of cathode ray tubes used in television[10].

References.

(1) C.I.E., 1931, p. 19.
T. Smith and J. Guild, "Trans. Opt. Soc.," 33, p. 73, 1931-32.
(2) J. Guild, "Trans. Opt. Soc.," 27, p. 106, 1925-26.

(3) R. Donaldson, "Proc. Phys. Soc.," 47, p. 1068, 1935.
(4) British Patent Application, No. 29435/3, October 29, 1936.
(5) J. G. Holmes, "Proc. Phys. Soc.," Vol. 47, p. 400, 1935-36.
(6) L. Bloch, "Naturwissenschaften," 20, p. 919, 1932.
(7) "Photoelectric Cells," Campbell and Ritchie, p. 212.
(8) J. Guild, "Trans. I.E.S.," Vol. 2, No. 9, p. 128, 1937.
(9) W. H. Coblentz, "Bull. Bur. of Std.," Vol. 7, p. 619, 1911.
(10) L. C. Jesty and G. T. Winch, "Trans. I.E.S.," Vol. 2, No. 8, p. 104, 1937.

APPENDIX.

CALCULATION OF RGB CO-ORDINATES OF PHOTOELECTRIC COLORIMETER IN TERMS OF X, Y, Z CO-ORDINATES OF C.I.E. SYSTEM.

$\lambda = .6438\mu$ $\quad .80R + .20G + 0B = .7223X + .2777Y + 0Z$ .....(a)
$\lambda = .546\mu$ $\quad .32_3R + .67_3G + 0B = .2738X + .7174Y + .0088Z$.(b)
$\lambda = .436\mu$ $\quad .17_3R + .03G + .79_3B = .1666X + .0089Y + .8245Z$.(c)

Eliminating G from (a) and (b).

$$.475R = .43279X + .04397Y - .00176Z.$$
$$\therefore \quad R = .9111X + .0926Y - .0037Z.$$

Substituting for R in (b).

$$.675G = -.0223X + .6873Y + .0100Z.$$
$$\therefore \quad G = -.0330X + 1.0182Y + .0148Z.$$

Substituting for R and G in (c).

$$.795B = .00815X - .03785Y + .8247Z.$$
$$\therefore \quad B = .0102X - .0476Y + 1.0374Z.$$

*CALCULATION OF THE CONSTANTS FOR A NOMOGRAM CONVERTING RGB OF PHOTOELECTRIC COLORIMETER TO XYZ OF C.I.E. SYSTEM.

Suppose the colour to be represented by

$$C = rR + gG + bB$$

where r, g and b are known and $r+g+b=1$. The original calibration of the colorimeter yields equations of the form

$$R = \rho_1 X + \rho_2 Y + \rho_3 Z$$
$$G = \gamma_1 X + \gamma_2 Y + \gamma_3 Z$$
$$B = \beta_1 X + \beta_2 Y + \beta_3 Z$$

In a nomogram of the form shown in Figure 7 the R, G and B scales will be at equal separation, the G scale being reversed and with half the unit of the R and B scales, so that $r+g+b=1$. If the total separation of the R and B scales is D, and the unit of these scales is d, the positions and units of the X, Y and Z scales can be shown to be as follows:—

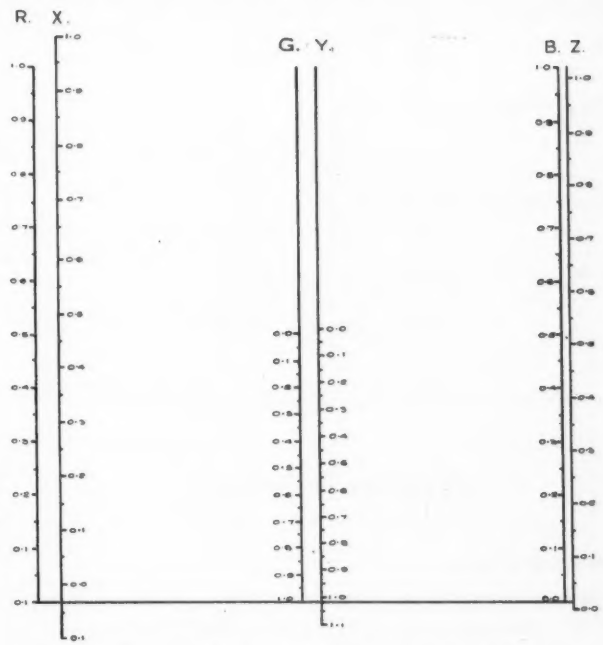

Fig. 7.—Nomogram for converting RGB Co-ordinates of Photoelectric Colorimeter to XYZ Co-ordinates of C.I.E. System.

Position of X scale $= \dfrac{(\beta_1 - \gamma_1)D}{(\rho_1 + \beta_1 - 2\gamma_1)}$ from R scale.

Position of zero on X scale $= -\gamma_1$

Unit distance on X scale $= \dfrac{d}{(\rho_1 + \beta_1 - 2\gamma_1)}$

Position of Y scale $= \dfrac{(\beta_2 - \gamma_2)D}{(\rho_2 + \beta_2 - 2\gamma_2)}$ from R scale.

Position of zero on Y scale $= -\gamma_2$

Unit distance on Y scale $= \dfrac{d}{(\rho + \beta_2 - 2\gamma_2)}$

Position of Z scale $= \dfrac{(\beta_3 - \gamma_3)D}{(\rho_3 + \beta_3 - 2\gamma_3)}$ from R scale.

Position of zero on Z scale $= -\gamma_3$

Unit distance on Z scale $= \dfrac{d}{(\rho_3 + \beta_3 - 2\gamma_3)}$

Using the following equations

$$R = 0.9111X + 0.0926Y - 0.0037Z.$$
$$G = -0.0330X + 1.0182Y + 0.0148Z.$$
$$B = 0.0102X - 0.0476Y + 1.0374Z.$$

the following constants of the nomogram are obtained:—

* This has been abstracted from the paper by J. G. Holmes (see reference 5).

Position of X scale from R scale

$$= \frac{(.0102 + .0330)\ 10}{(.9111 + .0102 + .066)} = +.439.$$

Unit distance on X scale

$$= \frac{1.0}{(.9111 + .0102 + .066)} = 1.012.$$

Position of zero on X scale

$= + .033 \equiv .0334$ with new unit.

Position of Y scale from R scale

$$= \frac{(- .0476 - 1.0182)\ 10}{(.0926 - .0476 - 2.0364)} = +5.35.$$

Unit distance on Y scale

$$= \frac{1.0}{(.0926 - .0476 - 2.0364)} = -.502.$$

Position of zero on Y scale

$= - 1.0182 \equiv -.512$ with new unit.

Position of Z scale from R scale

$$= \frac{(1.0374 - .0148)\ 10}{(- .0037 + 1.0374 - .0296)} = 10.17.$$

Unit distance on Z scale

$$= \frac{1.0}{(- .0037 + 1.0374 - .0296)} = .994.$$

Position of zero on Z scale

$= -.0148 \equiv - .0147$ with new unit.

Applications for Membership

(Continued from p. 136)

Elections Pending.

COUNTRY MEMBERS (*continued*):—

Skinner, J. P. .....195, Rock Street, SHEFFIELD.

Smith, A. G. .....6, Transmere Bye Pass, Guiseley, Nr. LEEDS.

Tate, W. K. .....The Sheppey Gas Co., The Broadway, Sheerness, KENT.

Thompson, W. G. ...8, Whirlow Court Road, SHEFFIELD, 11.

Trigt, S. van .....Purmersteenweg, 24, Purmerend, HOLLAND.

Wilde, A. .....149, Hyde Park Road, LEEDS, 6.

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Harris, H. W. .....30, Lidgett Park Avenue, Roundhay, Leeds, 8.

Pratt, A. S. R. .....4, Laisteridge Lane, BRADFORD.

Williams, O. G.....10, Dorset Avenue, LEEDS.

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Pates, K. G. .....2, Queen's Terrace, Otley Road, Guiseley, Nr. LEEDS.

Settle, W. E.....37, Ashtofts Mount, Guiseley, Nr. LEEDS.

Subbaranàn, M.....Engineering Student, Puvalur P.O.9 (via), Lalgudi, Trichinopoly (Dt.), S. INDIA.

Elections Completed.

At this meeting the names of those announced on May 19, which were published in the issue of the TRANSACTIONS (Vol. II., No. 6, June, 1937, p. 67), were presented again, and these applicants were formally declared members of the Society.

The Illuminating Engineering Society is not, as a body, responsible for the opinions expressed by individual authors or speakers.

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